Chapter 2
Plan Formulation and Economic Evaluation

2-1. Overview

A flood-damage-reduction plan includes measures that reduce damage by reducing discharge, reducing stage, or reducing damage susceptibility. For Federal projects, the objective of the plan is to solve the problem at hand in such a manner that the solution will "... contribute to national economic development (NED) consistent with protecting the Nation's environment, pursuant to national environmental statutes, applicable executive orders, and other Federal planning requirements (U.S. Water Resources Council (USWRC) 1983)." A planning study is conducted to determine (1) which measures to include in the plan, (2) where to locate the measures, (3) what size to make the measures, and (4) how to operate measures in order to satisfy the Federal objective and constraints. According to WRC guidelines, the study should lead decision makers to the optimal choice of which, where, what size, and how to operate by comparing "various alternative plans ...in a systematic manner." In Corps planning studies, this is accomplished by:

a. *Formulating* alternative plans that consist of combinations of measures, with various locations, sizes, and operating schemes. Engineer Manual (EM) 1110-2-1419 describes measures that might be included. ER 1105-2-100 provides guidance on formulating plans that are mixes of these measures. ER 1105-2-101 provides guidance on the use of risk-based analysis methods during the formulation process.

b. *Evaluating* the NED contribution and engineering performance of each plan. This document provides guidance on this evaluation.

c. *Comparing* the NED contribution, engineering performance, and satisfaction of environmental and policy requirements, thus leading to recommendation of a plan for implementation.

The search for the recommended plan is conducted in phases, as described in ER 1105-2-100. In the first phase, the *reconnaissance phase*, alternatives are formulated and evaluated in a preliminary manner to determine if at least one plan exists that (1) has positive net benefit, (2) is likely to satisfy the environmental-protection and performance standards, and (3) is acceptable to local interests. If such a plan can be identified, and if a local sponsor is willing to share the cost, the search for the recommended plan continues to the second phase, the *feasibility phase*. In that phase, the set of alternatives is refined and the search is narrowed. The evaluation is more rigorous, leading to identification of the recommended plan in sufficient detail that it can be implemented without significant change. In the third phase, the *pre-construction engineering and design study* (PED), design documents and plans and specifications necessary for implementation are prepared. Although applicable to some extent in all phases, the uncertainty analysis procedures described herein are intended for the feasibility phase. However, if plans change significantly between conduct of the feasibility and PED studies, reformulation is required. In that case, uncertainty analysis is required, consistent with requirements of a feasibility study.

2-2. Formulation

a. Plan formulation is the process of systematically reviewing the characteristics of the problem to identify promising candidate damage reduction measures or mixes of measures. The product of the formulation exercise is a set of alternative plans that are evaluated in progressively greater detail to identify a superior plan. This process is dynamic, as new alternatives may be revealed and added to the candidate list during the evaluation.

b. Corps planning, formulation, and the subsequent evaluation and selection take place in a public forum. The views and ideas of all stakeholders are solicited and incorporated in the plans formulated. To do so fairly and properly, Corps flood-damage reduction studies are conducted by multidisciplinary teams. Typically, such a team includes experts in planning, economics, hydrologic engineering, structural or geotechnical engineering, ecology, and public policy. Individually, these team members bring to bear their expertise in and knowledge of critical technical subjects. Jointly, the team members formulate candidate plans.

2-3. Traditional Economic Evaluation and Display

a. *NED contribution.*

(1) Once a set of candidate plans is formulated, each is evaluated using the NED objective and applicable environmental and policy constraints. In the case of flood-damage-reduction planning, the NED objective is measured by a plan's net benefit, NB, computed as

$$NB = (B_L + B_1 + B_{IR}) - C \qquad (2\text{-}1)$$

B_L is the *location benefit*, the value of making floodplain land available for new economic uses, such as shifting from agricultural to industrial use. B_I, the *intensification benefit*, is the value of intensifying use of the land, such as shifting from lower to higher-value or higher-yield crops. B_{IR}, the *inundation-reduction benefit*, is the value of reducing or modifying the flood losses to economic activity already using the floodplain land in the absence of any further action or plan. C is the total cost of implementing, operating, maintaining, repairing, replacing, and rehabilitating (OMRR&R) the plan. For comparison purposes, these benefits and costs are average values over the analysis period. This analysis period is the same for each alternative. The analysis period is the time over which any plan will have significant beneficial or adverse effects; or a period not to exceed 100 years (ER 1105-2-100).

(2) The basis for computation of the location, intensification, and inundation-reduction benefits is the *without-project* condition. This is defined as "...the land use and related conditions likely to occur under existing improvements, laws, and policies... (ER 1105-2-100)." The planning team must identify carefully this without-project baseline condition, and because of the need to account for both base and future benefits, it must be identified as a function of time. Identification for the base year condition is relatively straightforward: Basin attributes can be inventoried. For future year conditions, however, forecasts must be made. For example, to identify future without-project stage-damage functions, a study team might study zoning and floodplain development ordinances, land-use plans, and population projections. A most likely scenario is normally adopted for 20 to 30 years out.

(3) Once the without-project conditions are established, location benefit for a candidate plan is computed as the income of the newly available floodplain land with that plan (the *with-project* income) less the without-project income. Similarly, intensification benefit is with-project income from production on the same floodplain land less without-project production. The inundation-reduction benefit is

$$B_{IR} = (X_{without} - X_{with}) \tag{2-2}$$

in which $X_{without}$ = without-project economic flood-inundation damage; and X_{with} = economic damage if the plan is implemented. For urban areas, this damage commonly is estimated with a stage-damage function that correlates damage and stage; the function is based on surveys of floodplain property. Stage, in turn, is related to discharge with a stage-discharge function (also known as a rating curve). This function is derived empirically from measurements or conceptually with a hydraulics model. Various damage-reduction measures alter either the discharge, the corresponding stage, or damage incurred. Thus, to find the inundation-reduction benefit of a plan, damage for the with-project case is found using the without-project discharge, stage-discharge, and stage-damage functions. This value is subtracted from damage found using the without-project discharge and functions.

b. Annual values. The random nature of flooding complicates determination of inundation damage: It raises a question about which flood (or floods) to consider in the evaluation. For example, the structural components of a plan that eliminates all inundation damage in an average year may be too small to eliminate all damage in an extremely wet year and much larger than required in an extremely dry year. WRC guidelines address this problem by specifying use of expected flood damage for computation of the inundation-reduction benefit. Thus the equation for computing a plan's NED contribution can be rewritten as

$$NB = B_L + B_I + (E\,[X_{without}] - E\,[X_{with}]) - C \tag{2-3}$$

in which E [ ] denotes the expected value. This expected value considers the probability of occurrence of all floods, as described in further detail in Section 2.4.

c. Discounting and annualizing. WRC guidelines stipulate that benefits and costs "...are to be expressed in average annual equivalents by appropriate discounting and annualizing..." This computation is simple if conditions in the basin remain the same over the analysis period: In that case, the average annual benefits and costs will be the same each year. However, if conditions change with time, the benefits and cost will change. For example, if pumps for an interior-area protection component of a levee plan must be replaced every 10 years, the OMRR&R cost will not be uniform. In that case, a uniform annual cost must be computed. Procedures for computations in more complex cases are presented in James and Lee (1971) and other engineering economics texts.

d. Display. ER 1105-2-100 provides examples of tables for display of economic performance of alternative plans. The tables display benefits and cost by category for each alternative (Table 6-7 of the ER) and the temporal distribution of flood damage, for the without-project condition (Table 6-9), and with alternative plans (Table 6-8).

2-4. Inundation-Reduction Benefit Computation

a. Theoretical background.

(1) As noted earlier, the random nature of flood damage makes it impossible to predict the exact value of damage that would be incurred or prevented any year. Because of this, plan evaluation is based on large-sample or long-term statistical averages, also known as *expectations*. The expected value of inundation damage X can be computed as

$$E\ [X] = \int_{-\infty}^{\infty} x f_X\ (x)\ dx \tag{2-4}$$

in which $E[X]$ = expected value of damage; x = the random value of damage that occurs with probability $f_X(x)dx$. With this, all the information about the probability of occurrence of various magnitudes of damage is condensed into a single number by summing the products of all possible damage values and the likelihood of their occurrence.

(2) In the equation, $f_X(x)$ is referred to as the *probability density function* (PDF). In hydrologic engineering, an alternative representation of the same information, the so-called *cumulative distribution function* (CDF), is more commonly used. This is defined as

$$F_X\ [x] = \int_{-\infty}^{x} f_X\ (u)\ du \tag{2-5}$$

(3) This distribution function, also known as a *frequency or probability function*, defines the probability that annual maximum damage will not exceed a specified value X. Alternately, by exchanging the limits of integration, the CDF could define the probability that the damage will exceed a specified value. In either case, the CDF and PDF are related as

$$\frac{dF_X\ [X]}{dx} = f_X\ (x) \tag{2-6}$$

so the expected value can be computed as

$$E\ [X] = \int_{-\infty}^{\infty} x\ \frac{dF_X(x)}{dx}\ dx \tag{2-7}$$

$E[X]$ in the equation is the expected annual damage, commonly referred to as EAD.

b. Method of computation.

(1) Mechanically, then, finding the expected value of annual damage is equivalent to integrating the annual damage-cumulative probability function. The function can be integrated analytically if it is written as an equation, but this approach is of little value in a Corps study, as analytical forms are not available. In fact, the damage probability function required for expected-annual-damage computation is not available in any form. Theoretically, the function could be derived by collecting annual damage data over time and fitting a statistical model. In most cases, such damage data are not available or are very sparse.

(2) Alternatively, the damage-probability function can be derived via transformation of available hydrologic, hydraulic, and economic information, as illustrated by Figure 2-1. A discharge-probability function (Figure 2-1*a*) is developed. If stage and discharge are uniquely related, a rating function (Figure 2-1*b*) can be developed and the discharge-probability function can be transformed with this rating function to develop a stage-probability function. [This implies that the probability of exceeding the stage S that corresponds to discharge Q equals the probability of exceeding Q.] Similarly, if stage and damage are uniquely related, a stage-damage function (Figure 2-1*c*) can be developed, and the stage-probability function can be transformed with that function to yield the required damage-probability function. Finally, to compute the expected damage, the resulting damage-probability function is integrated. This can be accomplished using numerical techniques.

(3) As an alternative to transformation and integration, expected annual damage can be computed via sampling the functions shown in Figure 2-1. This procedure estimates expected annual damage by conducting a set of experiments. In each experiment, the distribution of annual maximum discharge is sampled randomly to generate an annual flood: the annual maximum discharge that occurred in an experimental "year." Then the annual damage is found via transformation with the stage-discharge and stage-damage functions. This is repeated until the running average of the annual damage values is

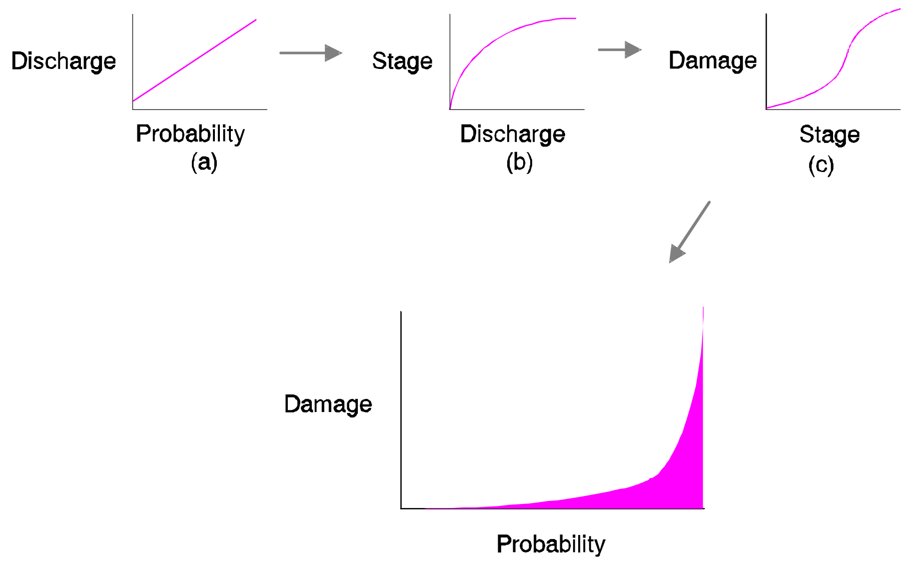

Figure 2-1. Illustration of transformation for traditional expected annual damage computation

not significantly changed (say by 1 percent) when more sample sets are taken. Finally, the average or expected value of all sampled annual damage values is computed. The procedure is illustrated in Figure 2-2.

2-5. Study Strategy

Proper administration of public funds requires that flood-damage-reduction studies be well planned and organized to ensure that the study will (a) provide the information required for decision making, (b) be completed on time, and (c) be completed within budget. To maximize the likelihood that this will happen, a study strategy should be developed before plan evaluation begins. At a minimum, this strategy must include:

(1) *Specification of a spatial referencing system.* Much of the data necessary for proper evaluation has a strong spatial characteristic. For efficiency, a common spatial referencing system should be specified and employed by all members of the multidisciplinary study team. This will ensure that, as necessary, it is possible to map, to cross-reference, and otherwise, to coordinate location of structures, bridges, and other critical floodplain elements.

(2) *Delineation of subbasins.* Hydrologic engineers will select subbasin boundaries based on location of stream gauges, changes in stream network density, changes in rainfall patterns, and for other scientific reasons. Based on this delineation, hydrologic engineering studies will yield discharge-probability and rating functions. This subbasin delineation, however, must also take into account the practical need to provide the information necessary for evaluation at locations consistent with alternatives formulated. For example, if a reservoir alternative is proposed, the subbasin delineation must be such that inflow and outflow probability functions can be developed at the proposed site of the reservoir.

(3) *Delineation of damage reaches for expected-annual-damage computation*. The damage potential for individual structures in a floodplain may be aggregated within spatially defined areas along the stream called damage reaches. Within each reach, an index location is identified at which exceedance probability is stage measured. Then flooding stage at the site of each structure is also related to stage at this index. Thus an aggregated function may be developed to relate all damage in the reach to stage at the single index. The boundaries of these damage reaches must be selected carefully to

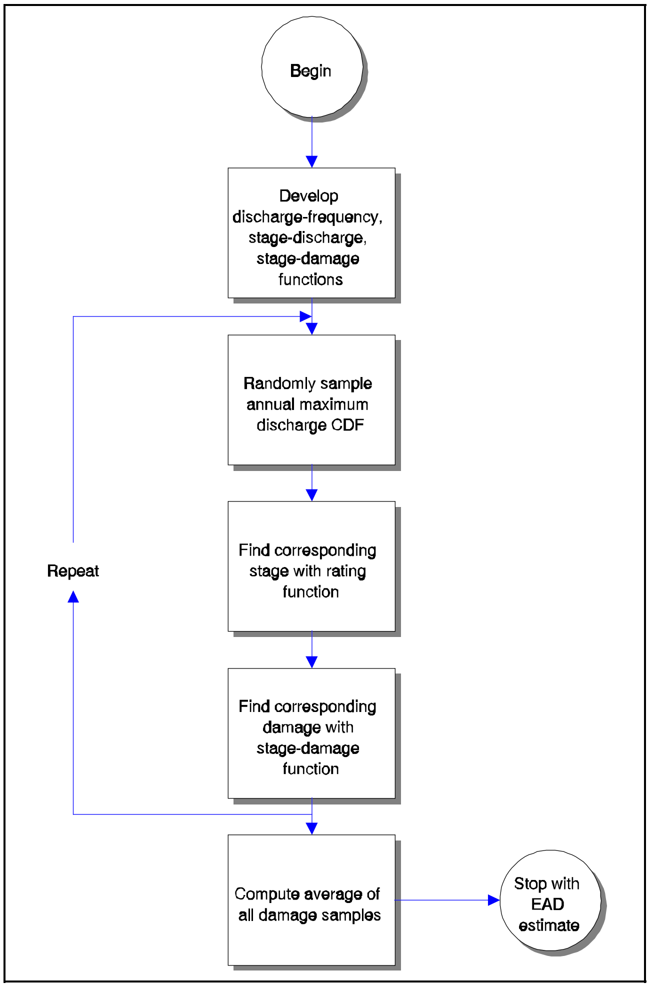

Figure 2-2. Flowchart for expected annual damage computation via annual-flood sampling (model and parameter uncertainty not considered)

ensure that information necessary for proper evaluation of plans proposed is available. For example, if a candidate plan includes channel modifications for a stream reach, evaluation of that plan will be most convenient if a damage reach has boundaries that correspond to the boundaries of the stream reach.

2-6. Uncertainty Description and Analysis

a. Sources of uncertainty. In planning, decisions are made with information that is uncertain. In flood-damage-reduction planning, these uncertainties include:

(1) Uncertainty about future hydrologic events, including future streamflow and rainfall. In the case of discharge-probability analysis, this includes uncertainty regarding the choice of a statistical distribution and uncertainty regarding values of parameters of the distribution.

(2) Uncertainty that arises from the use of simplified models to describe complex hydraulic phenomena, from the lack of detailed geometric data, from misalignment of a hydraulic structure, from material variability, and from errors in estimating slope and roughness factors.

(3) Economic and social uncertainty, including lack of information about the relationship between depth and inundation damage, lack of accuracy in estimating structure values and locations, and lack of ability to predict how the public will respond to a flood.

(4) Uncertainty about structural and geotechnical performance of water-control measures when these are subjected to rare stresses and loads caused by floods.

b. Describing uncertainty.

(1) Traditionally in Corps planning studies, uncertainties have not been considered explicitly in plan formulation and evaluation. Instead the uncertainties have been accounted for implicitly with arbitrarily selected factors of safety and for such features as levees with freeboard. Quantitative risk analysis describes the uncertainties, and permits evaluation of their impact. In simple terms, this description defines the true value of any quantity of interest in the functions shown in Figure 2-1 as the algebraic sum of the value predicted with the best models and parameters and the error introduced because these models and parameters are not perfect. When reasonable, a statistical distribution is developed to describe the error. Such a distribution might reveal that the probability is 0.10 that the error in stage predicted with a rating function is greater than 0.7 m or that the probability is 0.05 that the error in predicting the 0.01-probability discharge is greater that 500 m^3/s.

(2) Chapters 3, 4, and 5 provide guidance on describing uncertainty in functions necessary for flood-damage reduction plan evaluation. Once this uncertainty is described, the impact on evaluation of plan performance can be determined. Two broad categories of techniques are suggested for this uncertainty analysis, depending upon the nature of the uncertainties:

(a) *Simulation or sampling.* This includes (a) expansion of the annual-flood sampling technique to incorporate the descriptions of uncertainty, sampling from each; (b) modification of the sampling technique so that each sample is not a flood, but instead is an equally likely discharge-probability function, rating function, or stage-damage function with which expected annual damage can be computed, and (c) modification of annual-flood sampling technique to generate life-cycle sized samples that are evaluated.

(b) *Sensitivity analysis.* Here, the evaluation is based on specified alternative future conditions and evaluated with traditional procedures. These alternative futures include common and uncommon events, thus exposing the full range of performance of alternatives.

c. Uncertainty analysis via annual-flood sampling. This method computes expected annual damage as illustrated by Figure 2-2, except that an error component (ε) is added to the predicted discharge, stage, and damage at each step. The error cannot be predicted, it can only be described. To describe it, a random sample from the probability distribution of each error is drawn. This assumes that (1) the error in each function is random, and (2) the errors in predicting damage in successive floods are not correlated. Table 2-1 shows the steps of the computations.

d. Uncertainty analysis via function sampling. An alternative to the annual-flood sampling method is to compute expected annual damage by sampling randomly from amongst likely discharge-probability, rating, and stage-damage functions—functions that include explicitly the error components. Table 2-2 shows how this may be accomplished.

Table 2-1
Annual-Flood Sampling Procedure

Step	Task
1	Sample the discharge-probability function to generate an annual flood. This amounts to drawing at random a number between 0.000000 and 1.000000 to represent the probability of exceedance of the annual maximum discharge and referring to the median probability function to find the corresponding annual maximum discharge.
2	Add a random component to represent uncertainty in the discharge-probability function; that is, the uncertainty in predicting discharge for the given exceedance probability from Step 1. This is accomplished by developing and sampling randomly from the probability function that describes the uncertainty. For example, as noted in Chapter 3, the uncertainty or error is described with a non-central *t* distribution for discharge-probability functions fitted with the log Pearson type III distribution.
3	Find the stage corresponding to the discharge plus error from Step 3.
4	Add a random component to represent the uncertainty in predicting stage for the given discharge. To do so, define the probability density function of stage error, as described in Chapter 4 and sample randomly from it.
5	Find the damage corresponding to the stage plus error from step 4.
6	Add a random component to represent uncertainty in predicting damage for the given stage. To do so, define the probability density function of damage error, generate a random number to represent the probability of damage error, refer to the error probability function to find the error magnitude, and add this to the result of Step 5.
7	Repeat Steps 1-6. The repetition should continue until the average of the damage estimates stabilizes.
8	Compute necessary statistics of the damage estimates, including the average. This average is the required expected annual damage.

Table 2-2
Function Sampling Procedure

Step	Task
1	Select, at random, a discharge-probability function from amongst those possible, given the uncertainty associated with definition of the probability function for a given sample. This selected probability function will be the median probability function plus an error component that represents uncertainty in the probability function.
2	Select, at random, a stage-discharge function from amongst those possible, given the uncertainty associated with definition of this rating function. Again, this will be the median stage-discharge function plus an error component.
3	Select, at random, a stage-damage function from amongst those possible, given the uncertainty associated with definition of the stage-damage function. This function will be the median stage-damage function plus an error component.
4	Use the results of Steps 2 and 3 to transform the discharge-probability function of Step 1, thus developing a damage probability function.
5	Integrate the damage probability function to estimate expected annual damage. Call this a *sample* of expected annual damage.
6	Repeat Steps 1-5 to expand the expected annual damage sample set.
7	Compute the average and other necessary statistics of the expected annual damage estimates.